Cascading Failure in the topology models

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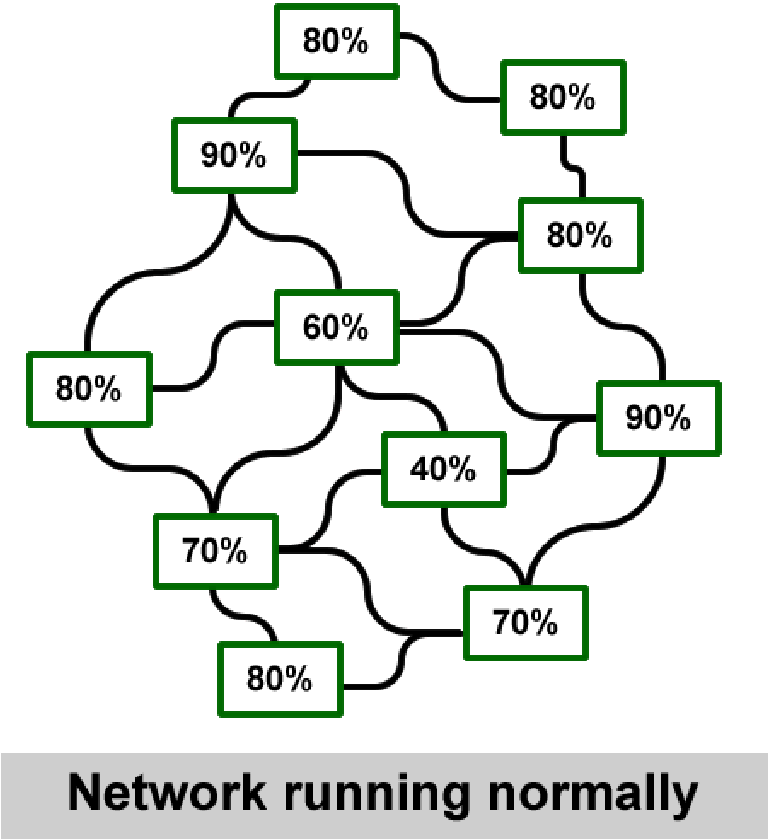
What is Cascading Failure?

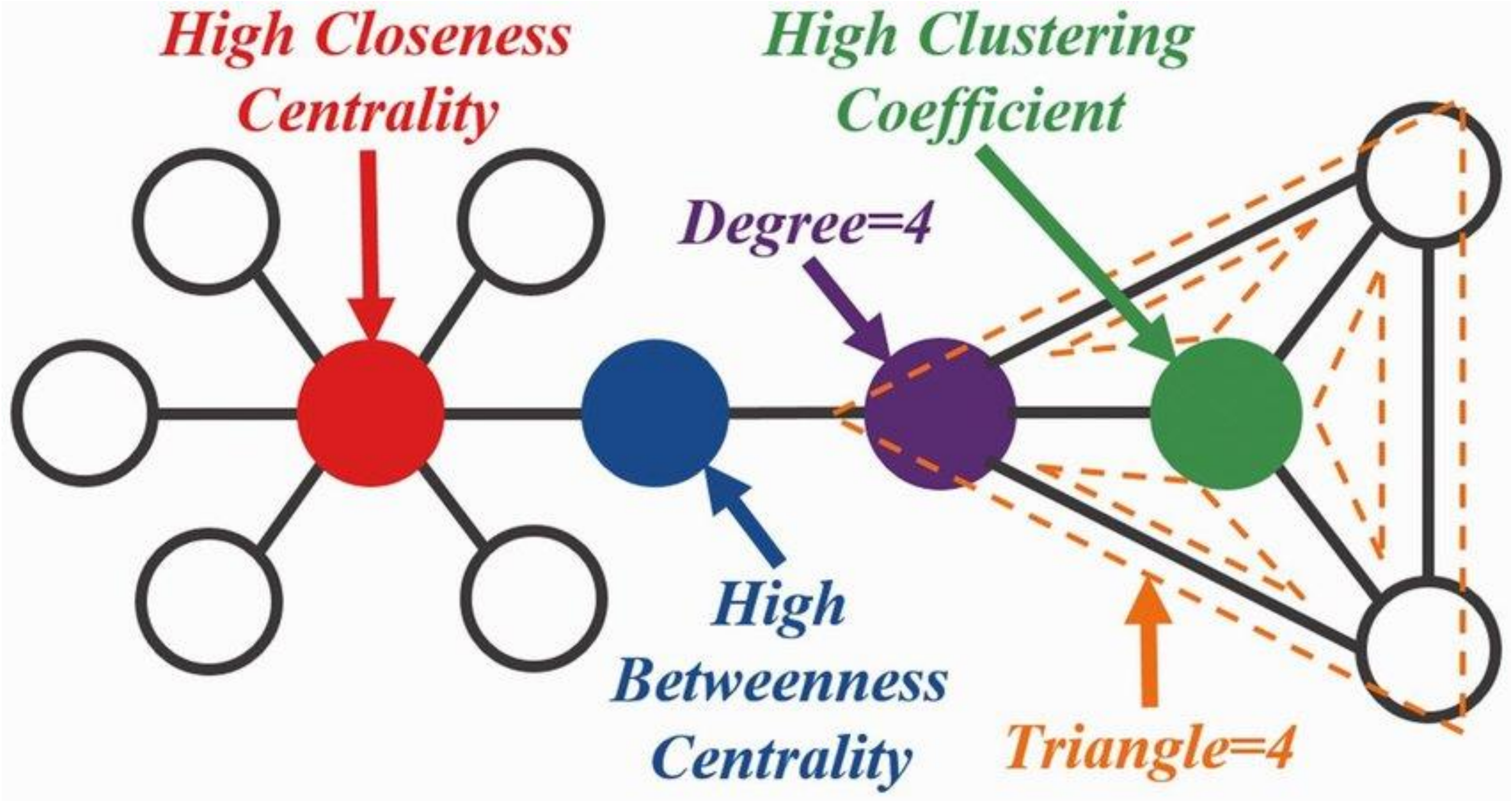


- is a process in a system of interconnected parts in which the failure of one or few parts can trigger the failure of other parts and so on.
- Cascading failures may occur when one part of the system fails. When this happens, other parts must then compensate for the failed component.

Cascading Failure in Power Grid

- When one of the elements fails (completely or partially) and shifts its load to nearby elements in the system. Those nearby elements are then pushed beyond their capacity, so they become overloaded and shift their load onto other elements.
- Cascading failures are the consequence of the collective dynamics of the complex power grid. Large scale cascades are typically due to propagation of a local failure into the global network.

Topological models



Adjacency Matrix

- Any graph or network has two basic components – nodes and edges.
- An unweighted
- network can be represented as an adjacency matrix (A). Any element of adjacency matrix (A) a_{ij} , is given as
- $a_{ij} \begin{cases} 1\,, & if\ i\ \neq\ j\ and\ i\ and\ j\ nodes\ are\ connected\ by\ edge \\ 0\,, & if\ i\ \neq\ j\ and\ i\ and\ j\ nodes\ are\ not\ connected \\ 0\,, & if\ i\ =\ j \end{cases}$

Node Degrees Distribution（度中心性）

- Defined as the number of links incident upon a node. The degree of any node i is represented by :

$$k_i = \sum_j a_{ij}$$

- The probability of degree distribution is represented by

$$P(k) = \frac{N(k)}{\sum N(k)}$$

- where N(k) is the number of nodes in the network with degree k.

Closeness Centrality (接近中心性)

- The proximity between one node and other nodes in the network. Calculated as the reciprocal of the sum of the length of the shortest paths between the node and all other nodes in the graph. Thus, the more central a node is, the closer it is to all other nodes.

$$C(x) = \frac{1}{\sum_y d(y,x)}$$

- Where d (y, x) is the distance between node x and y.

Betweenness Centrality (中介中心性)

- A measure of centrality in a graph based on shortest paths.

$$C_B(v) = \sum_{s \neq v \neq t \in V} \frac{\sigma_{st}(v)}{\sigma_{st}}$$

Where σ_{st} is total number of shortest paths from node s to node t and $\sigma_{st}(v)$ is the number of those paths that pass through v.

Clustering Coefficient

- The clustering coefficient (C) is a measure of local cohesiveness. Traditionally the clustering coefficient C_i of a node i is the ratio between the total number (e_i) of the edges actually connecting its nearest neighbors to the i^{th} node and the total number of all possible edges between all these nearest neighbors [$\frac{k_i(k_i-1)}{2}$; if the i^{th} vertex has k_i neighbors] and is given by

$$C_i = \frac{2e_i}{k_i(k_i - 1)}$$

where e_i is the total number of edges actually connecting the i^{th} node's nearest neighbors. Then the clustering coefficient of a network is the average of its all individual C_i 's.

Characteristic Path Length

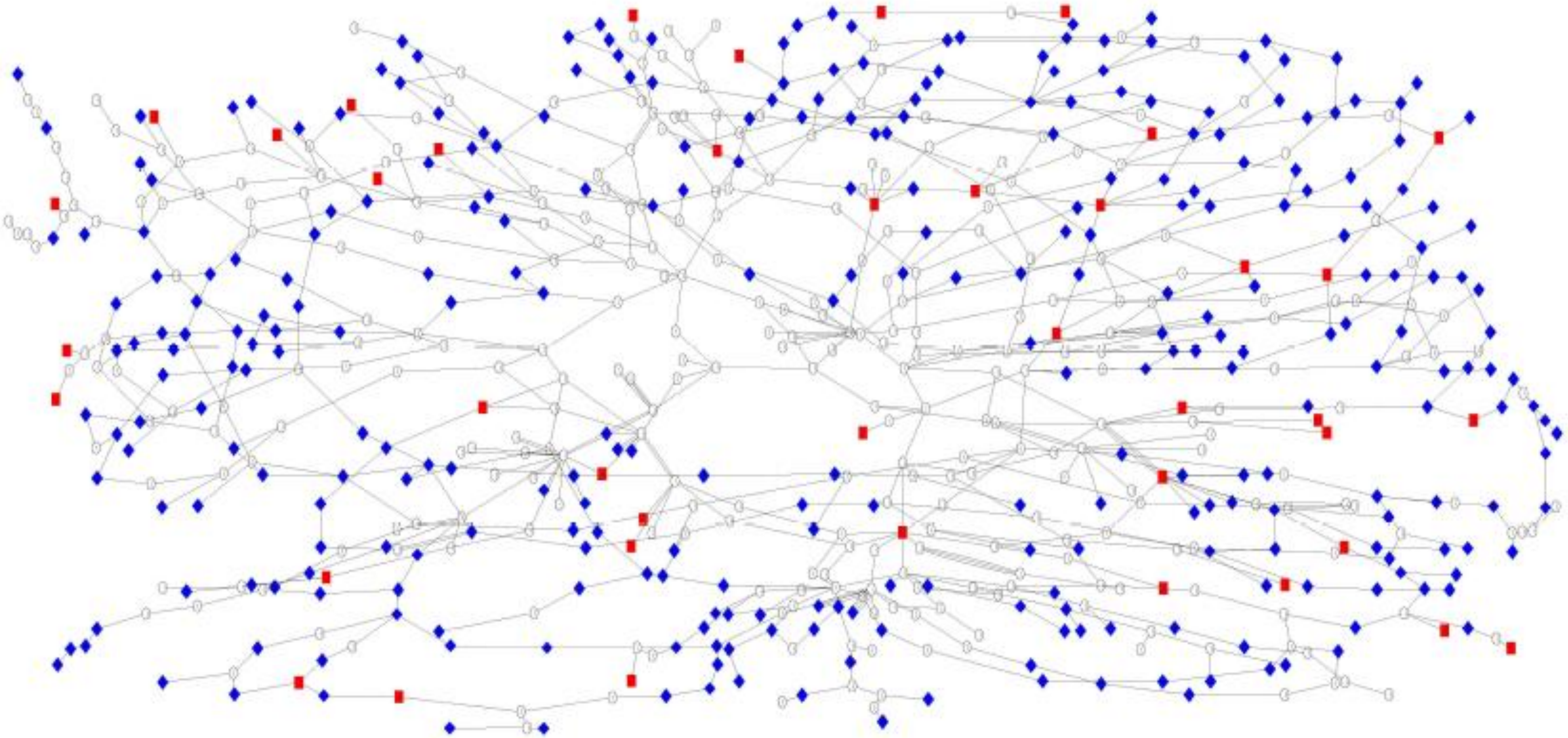
- The characteristic path length (L) of a network is the shortest path length between two nodes averaged over all pairs of nodes and is given by

$$L = \frac{\sum_i \sum_j L_{i,j}}{N(N-1)}$$

Where $L_{i,j}$ is the shortest path length between i^{th} node and j^{th} node.

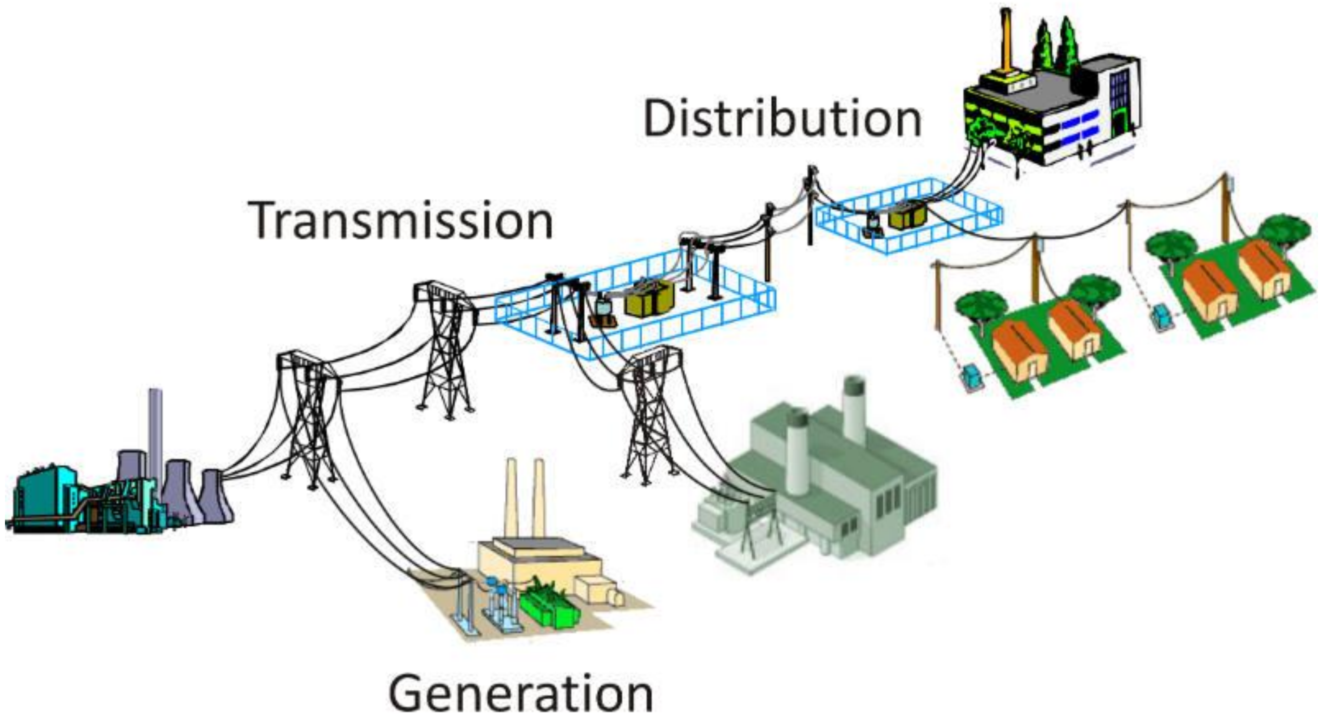
- Higher characteristic path length implies network is almost in liner chain and lower characteristic path length shows the network is in compact form.

Topology of A Real Power Grid



Power Grid Topology

- Distribution System : No generators are connected to such nodes, and in the topological structure each node is connected to only one single edge. Electricity is sent to consumers from such distribution nodes through low voltage transmission lines.
- Generation System : These nodes are connected to generators via transformers in real power grid. They are the sources of electric energy.
- Transmission System : No generators are connected to such nodes either, but in the topological structure each node is connected to more than one edge.



Robustness and vulnerability analysis

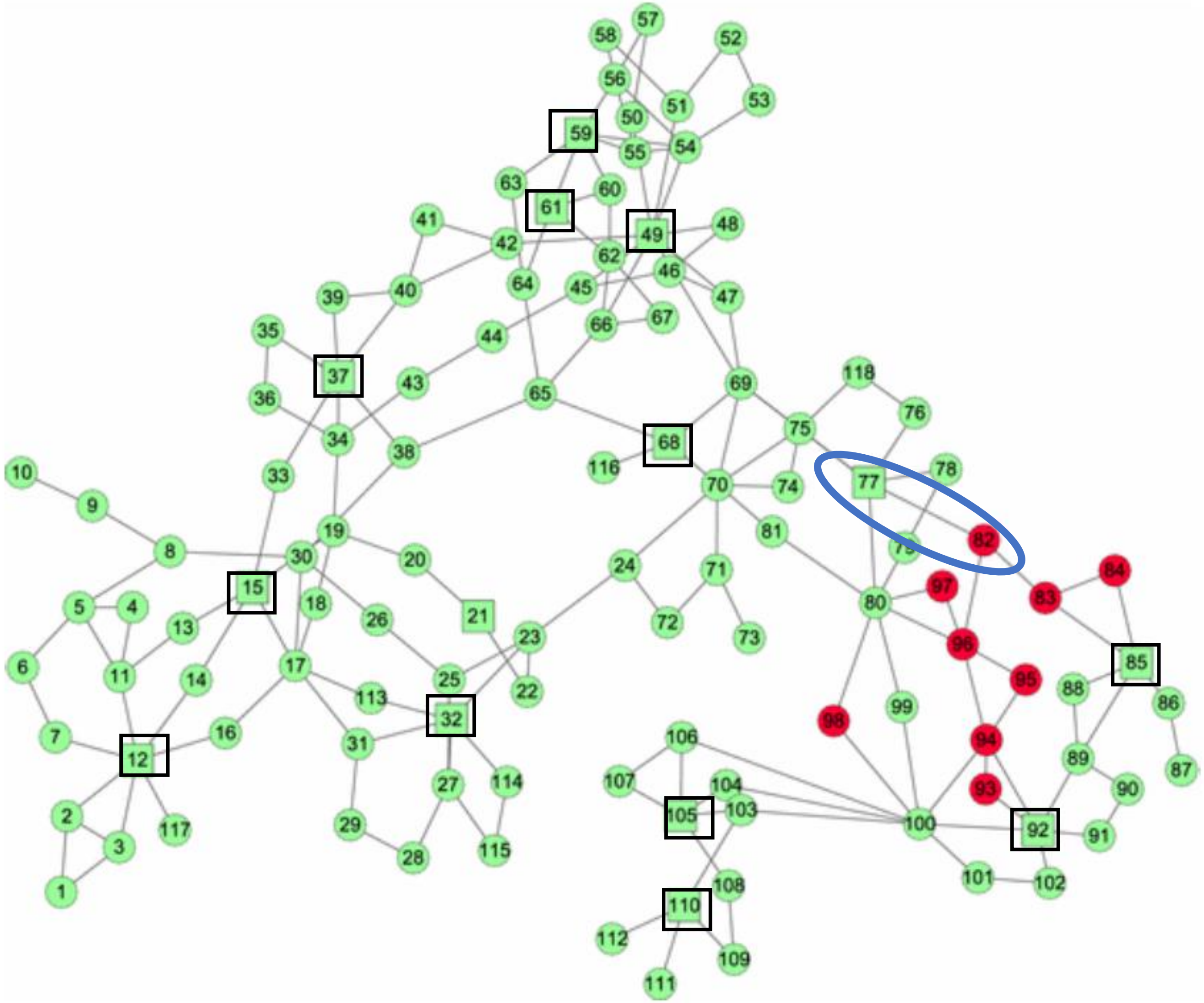
Concept	Definition	Ref.
Reliability	Probability that an electric power grid can perform a required function under given conditions for a given time interval (IEC definition).	[45]
	The probability of its satisfactory operation over the long run (IEEE definition).	[48]
Disturbance	An unexpected event that produces an anomalous system condition.	[45]
Contingency	The unexpected failure or outage of a network component, such as a generator, transmission line, or other electrical element.	[45]
Robustness	Degree to which a network is able to withstand an *unexpected* event without degradation in performance. It quantifies how much damage occurs as a consequence of such unexpected perturbation.	[49]
Vulnerability	The lack of robustness. Vulnerability is often used to score low reliability of power grids. It can be quantitatively defined by Equation (1).	[12]
Resilience	The ability of a power system to recover quickly after a disaster or, more generally, the ability of anticipating to extraordinary, high-impact, low-probability events, quickly recovering from these disruptive events, and adapting its operation and structure for preventing or mitigating the impact of similar events in the future.	[45]
Resilience *vs.* robustness	Robustness measures *how much* damage occurs as a consequence of an unexpected perturbation, while resilience measures *how quickly* the network can retrieve from such damage.	[49]
Resilience *vs.* reliability	Resilience is related to *low probability*, *high impact* events. It is a dynamic concept. Reliability is related to *high probability*, *low impact* events. It is a static concept.	[41,49]
Stability	The ability to maintain or to recover a state of equilibrium after disturbances or contingencies.	[40]
Critical Infrastructure	Infrastructure whose unavailability or destruction would have a extensive impact on economy, Government services and, in general, on everyday life, with severe consequences for a nation. Examples of critical infrastructures are power grids, telecommunication networks, transportation networks, water supply systems and natural gas and oil pipelines.	[50–53]

Robustness and Vulnerability Analysis

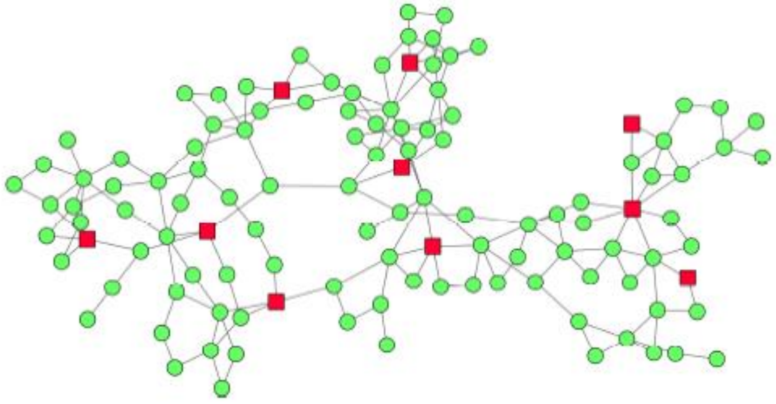
- Using Monte Carlo method to simulate all possible contingencies .
- Using Markov chain model to study the propagation dynamics of the entire power networks.
- Using the model that is derived from admittance model with two new robustness metrics percentage of unserved nodes (PUN) and percentage of noncritical links (PNL)

Simulation of cascading failure triggered by breakdown of transmission line (77, 82) of IEEE 118 bus. Squares are generators.

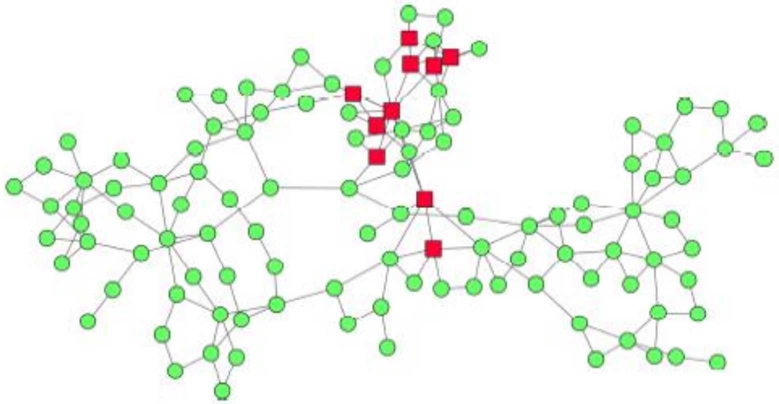
Red nodes are unserved nodes.



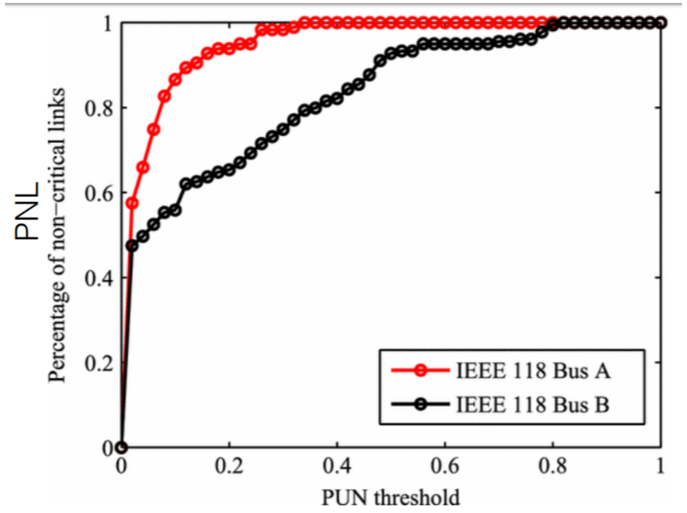
Effect of changing location of generators



(a)



(b)



Robustness assessment of IEEE 118 Bus A and B. Buses A and B only differ in the location of generators, with Bus A has more decentralized distribution of generators.

The result showed that for a given number (percentage) of available generators in a power system, the decentralized generator locations may greatly increase the robustness of the power grid.

Strategies to Improve Robustness

- Intentional Islanding
- Smart Addition of Links
- Hybrid Power Grids.
- Smart Grids

Mitigation and prevention of cascading

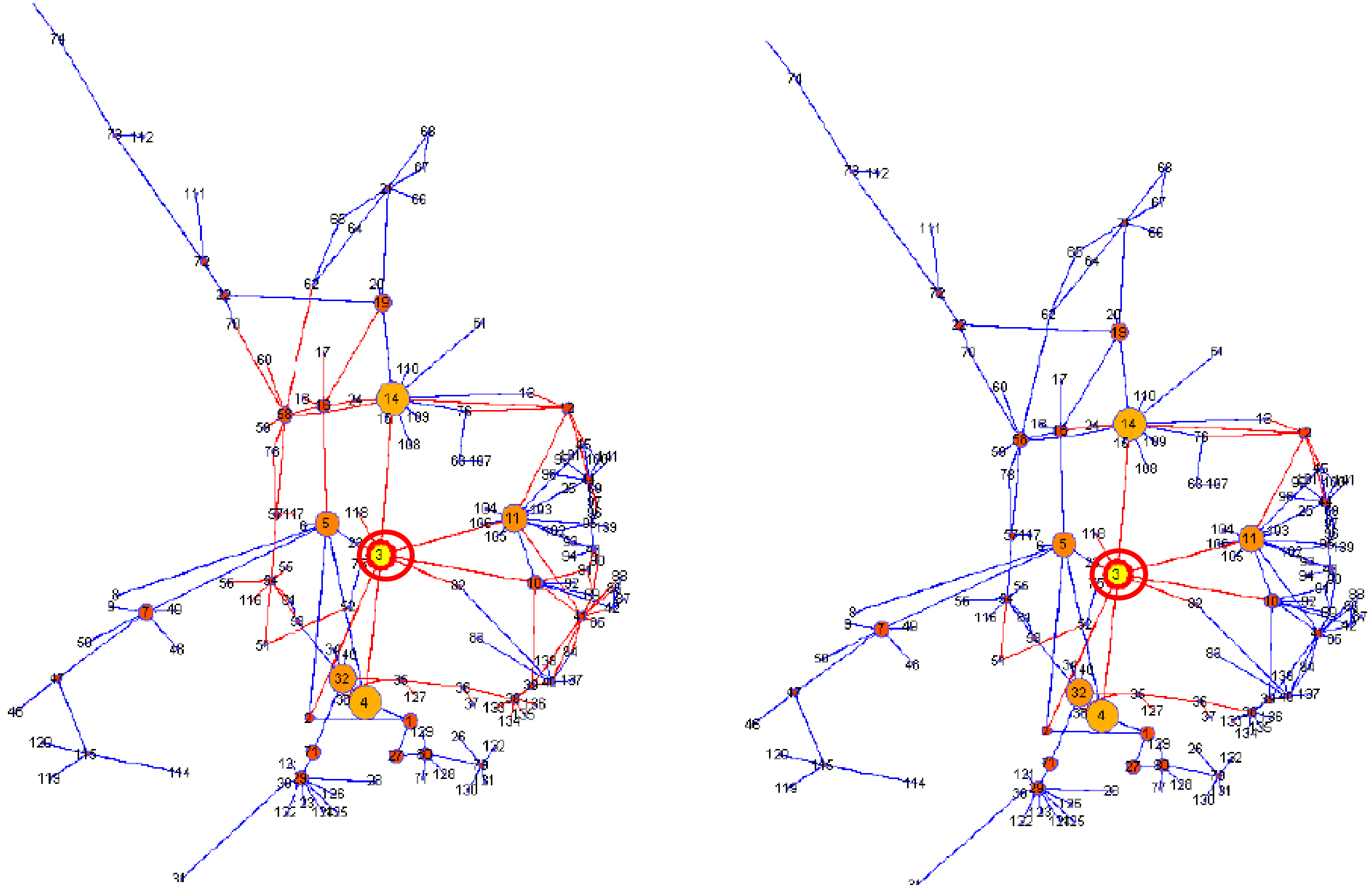
- Mitigation approach aims at reducing the impact of cascading failure by load shedding, line switching or some other remedial actions.
- Prevention of the cascading utilizes some fast response remedial actions at each stage of the cascading to prevent or at least mitigate the spread of the cascading
- Homogeneous Load Reduction
- Targeted Range-Based Load Reduction
- Distributed Renewable Sources in combination with Islanding

- The comparison method are Characteristics path length and clustering coefficient.

Dynamical model

- Evaluate the relation between the size and scope of blackouts due to node failures and the level of load of the network relatively to its capacity, which may be thought of as a measure of the proximity of the system state to its operational limit.

Dynamical model



(left) Cascading failure due to the removal of the node with highest load(node 3. Circled with red line) for n = 1.5:38.33% of the transmission line are tripped offline (in red)
(right) Cascading failure due to the removal of the node with highest load(node 3. Circled with red line) for n = 2.6.5:13.89% of the transmission line are tripped offline (in red)

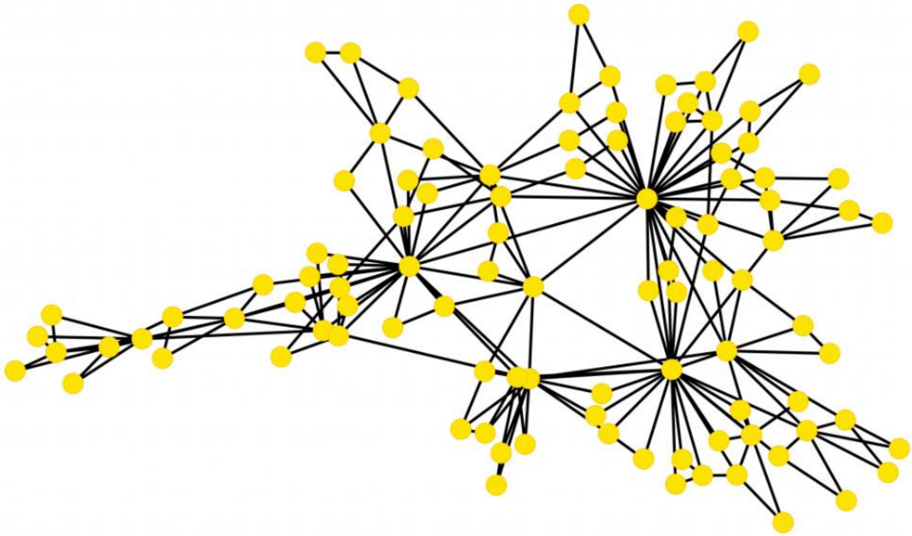
same topological structure can behave quite differently to individual failures, depending on the spare capacity of the remaining nodes and links.

Complex network perspective

- Complex Network

Node

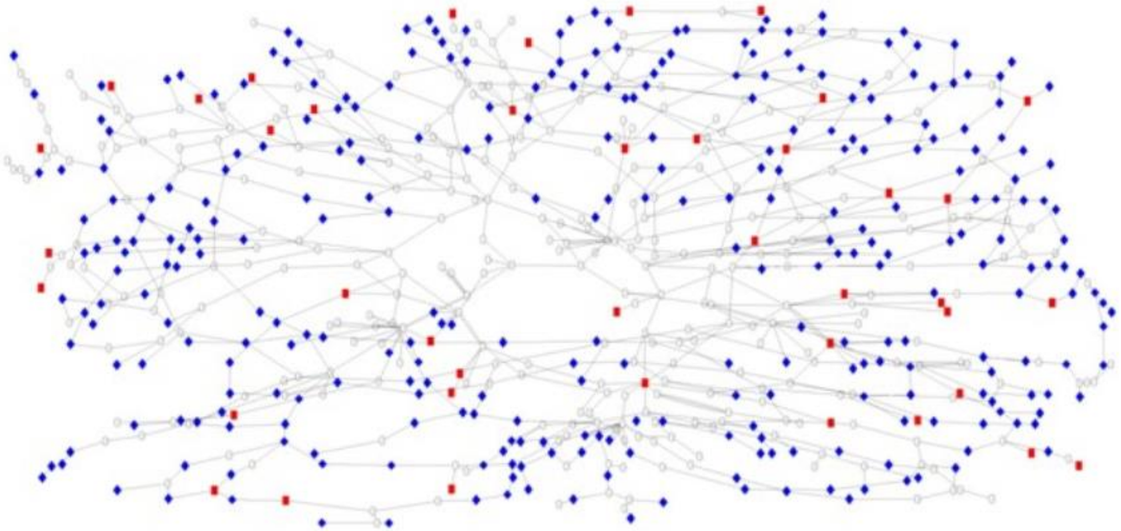
Link



- Power Grid

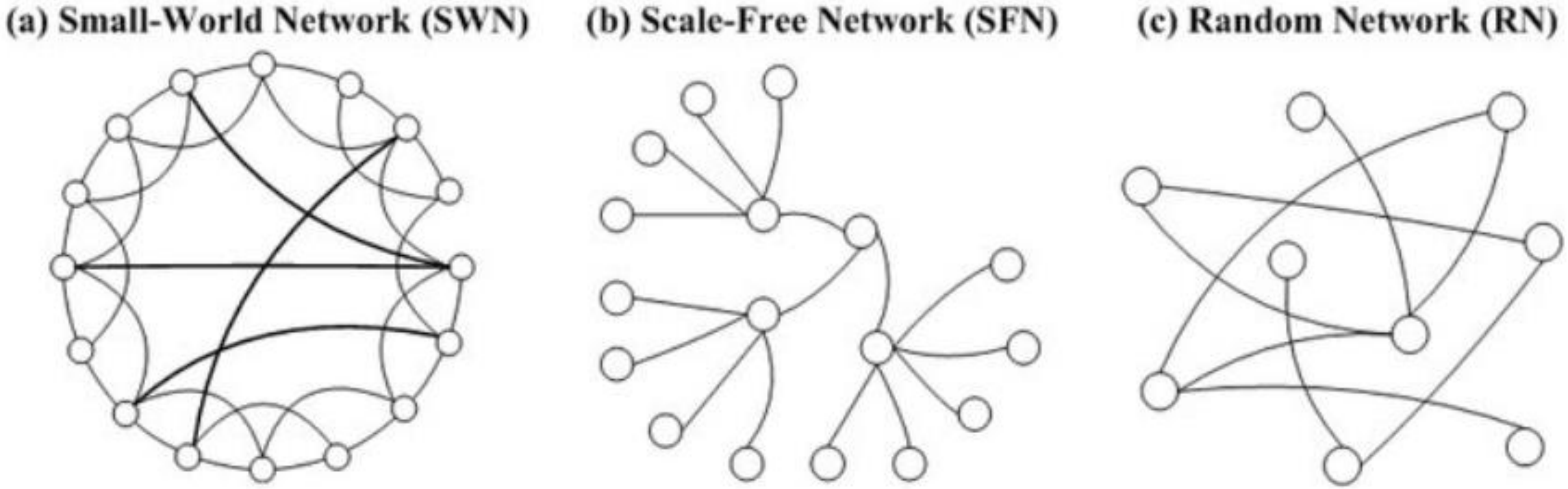
Generators, Transformers, Loads

Transmission lines

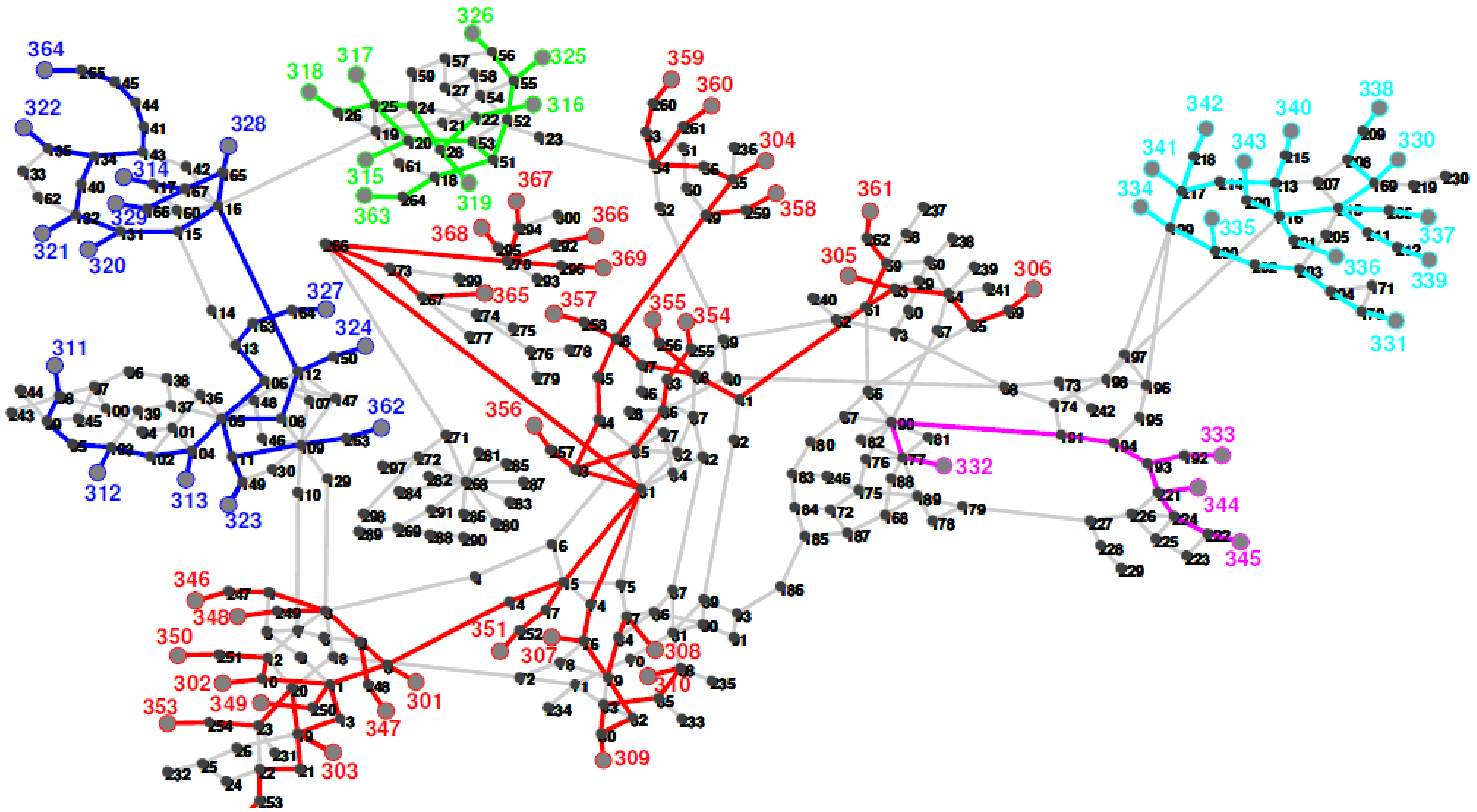


Complex Network Diagram

- Random graph
- Small-world
- Scale free



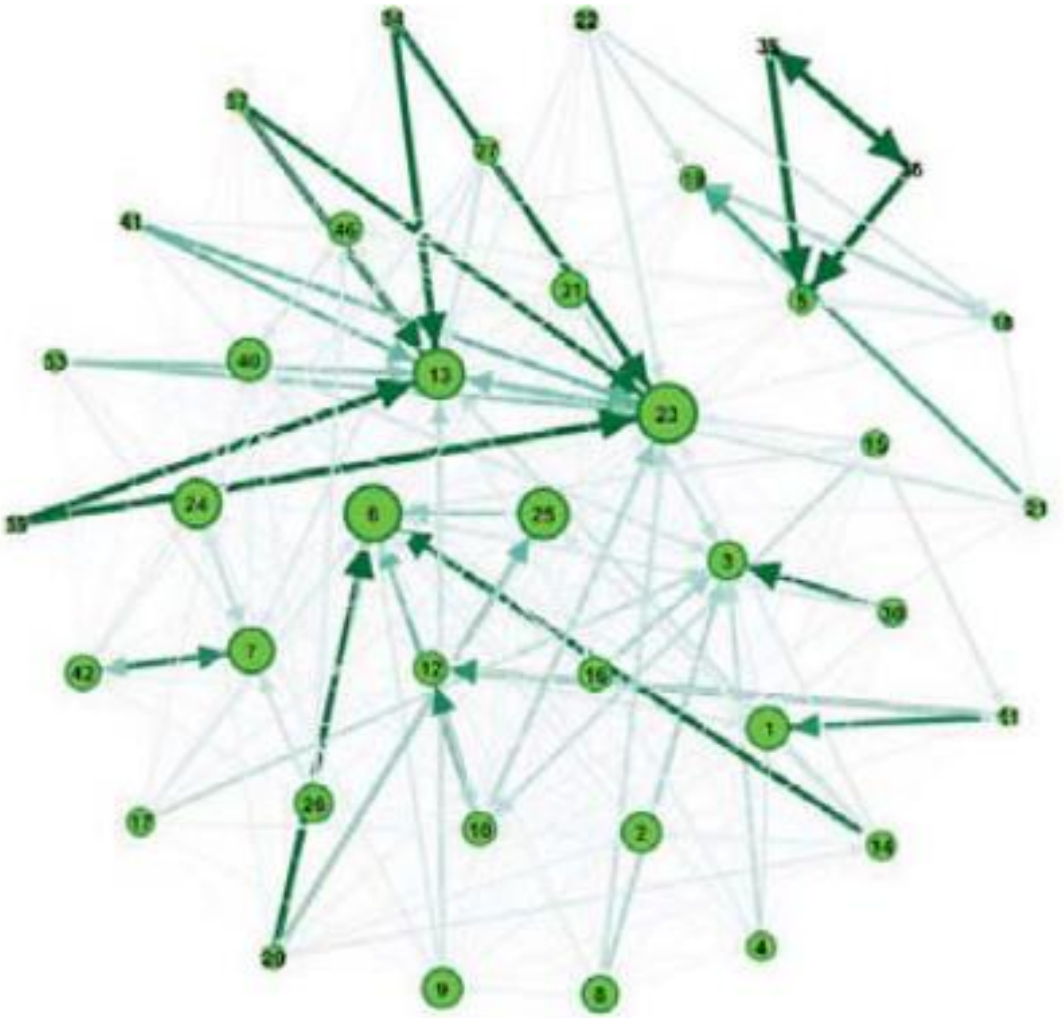
ICI algorithm based on a Linear Programming (LP)



proposes a novel ICI algorithm based on a Linear Programming (LP) formulation that directly determines an islanding solution with minimal power-flow disruption for any given number of islands, while ensuring that each island contains only coherent generators.

Objective : To improve time execution and effectiveness

Sequential Pattern Mining



applies sequential pattern mining technology to cascading failure analysis and this existing works pay more attention to vulnerable lines and high-risk path, which are hard to explain the overall propagation characteristic of cascading failure.

Summary of analyze synthetic topologies as key study cases

Reference	Order N	Size M	ND	B	Attack strategy	w/u?	Electrical concepts into the CN approach	Metrics/indicators used in vulnerability analysis
[17]	SN	SN	◇	◇	NA	u	–	ℓ, G
[141]	4941	–	◇	◇	NA	u	–	ℓ, G
[147]	14100	19660	◇	◇	NA	u	–	ℓ, Connectivity loss
[145]	14100	19660	◇	◇	NA	u	–	ℓ, E
[150]	3000	12000	◇	◇	NA	u	–	ℓ, G
[20]	3000	3800	◇		NA	u	–	ℓ, G
[19]	3000	3800	◇		NA	u	–	ℓ, G, ENS, TLP
[111]	4800	5500	◇		NA	u	–	ℓ, $\mathcal{C}$, G
[152]	380	570			NA, LA	u	–	D
[154]	6400	8700			NA	u	–	ℓ, $\mathcal{C}$
[155]	370	570	◇		LA	u	–	ℓ, $\mathcal{C}$
[147]	14000	19600	◇	◇	NA	u	–	Connectivity loss
[151]	31400	–	◇		NA, EA	u	–	Probability of load loss
[156]	2700	3300	◇		NA	u	–	Motifs (sub-graph) size ENS, TPL, RT
[84]	8500	13900	◇		NA	u	–	G
[159]	4900	6600			NA	u	–	S_N
[107]	940	1260			NA	u	–	Blackout size
[149]	4940	6600	◇	◇	NA	u	–	G
[117]	4850	5300	◇	◇	NA	both	–	ℓ, G
[148]	340	520	◇	◇	NA	w	–	E
[153]	14000	19600			NA	w	–	E, D
[35]	550	700			NA	w	Impedance, DC flow	E, $\mathcal{A}$, overload
[85]	32	420			NA, LA	w	Impedance, DC flow	$\mathcal{B}_E$, ENS
[188]	90	120			LA	w	Impedance, DC flow	E, $\mathcal{A}$
[169]	200	400		◇	LA	w	Line impedance, DC flow	Overload, cascade
[87]	2930	6570		◇	NA	w	Line impedance, DC power flow	C_D^E
[173]	29500	50000			NA	w	Line impedance and DC flow	ℓ, connectivity level
[172]	550	800		◇	NA	w	DC flow	Connectivity, TLP
[7]	210	320		◇	NA	both	DC and AC power flow	Blackout size, $\mathcal{C}$, ℓ
[174]	900	1150	◇	◇	NA	w	Line reactance	Loss of load, ℓ
[15]	570	870	◇	◇	NA	w	Active, reactive power loads	Loss of load
[175]	SN	SN	◇	◇	NA	w	AC model	$\overline{v}$, S, LD
[170]	2560	2890			NA, LA	w	Impedance	Largest power supply region
[181]	300	410	◇		NA	both	Line impedance	Impedance matrix sensitivity
[184]	150	46			NA	w	Line reactance, active power	E
[171]	39	46			NA	w	Line admittance, power flow	Flow availability
[30]	240	310			NA, LA	w	AC power flow model	C_D^E, C_B^E, ENS

a Summarize of metrics and their corresponding equations, references and approaches

Metric	Equation or definition	Reference
Average path length, ℓ	(4)	[61]
Clustering coefficient, $\mathcal{C}$	(5)	[57]
Size of the largest connected component, G	(6)	[61]
Efficiency, E (definition 1)	(7)	[140]
Network Efficiency, E (definition 2)	(13)	[153]
Betweenness centrality, $C_B(v) \equiv \mathcal{B}_v$	(9)	[61]
Degree centrality, C_D	(10)	[30]
Damage, D	(14)	[153]
Normalized avalanche size, S_N	(15)	[162]
Geodesic vulnerability, $\overline{v}$	(20)	[175]
Impact on connectivity, S	(21)	[175]
Connectivity loss	Average decrease in the number of generators connected to a distributing substation	[153]
Connectivity level	Average fraction of generators connected by each load substation	[153]
Backup capacity, P_B	Additional link capacity (overcapacity) that needs to be supplied to secure the proper network operation when the most loaded link suffers from a failure or attack	[21]
Load shedding, LS	(22)	[175]
Electrical centrality, c_a	(23)	[173,181]
Electrical distance, $\mathbf{D}$	(25)	[182,183]
Electrical degree centrality (def. 1), $C_D^E(i)$	(26)	[115,118,119,186]
Electrical degree centrality (def. 2), $C_D^E(i)$	(28)	[87]
Electrical betweenness centrality, $C_B^E(i)$	(27)	[34,115]
Electrical betweenness, $\mathcal{B}_E$	(30)	[8,78,85,168]
Net-ability, $\mathcal{A}$	(32)	[8,78,168]
Entropic degree, $\mathcal{S}_i$	(34)	[8,78,168]
Effective graph resistance, R_G	(29)	[5,187]

Note:

- 一条线故障，可能引发其他线路不稳定，不能说故障
- 发电量都是在变化，潮流在变化，故障在线路的位置也可能变化，导致故障的大小也不一样
- 因为每天的潮流是不一样的，所以在不同潮流下，故障一条线，可能引发的其他线路故障可能是不一样的